

## **Final Technical Report**

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Title:  
**Workshop on Nevada 3-D Seismic Community Velocity Models**

### **NEHRP Element(s):**

ELEMENT I: National and regional earthquake hazards assessments.

ELEMENT IV. Earthquake safety policy.

**Keywords:** Site effects, Basin effects, Seismic modeling, Ground motions,  
Seismic zonation, Engineering seismology

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## **Workshop on Nevada 3-D Seismic Community Velocity Models**

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### **NON-TECHNICAL ABSTRACT**

The USGS has been conducting research into physics-based modeling of shaking from scenario earthquakes for Seattle and Salt Lake City, in concert with similar efforts for northern and southern California. Since the USGS-NEHRP program has construction of new earthquake-hazard maps for Reno and then Las Vegas as top regional priorities, they have generously funded the formation of a broad-based working group to start up a physics-based shaking-prediction effort for Nevada.

Such scenario modeling requires assembling available geological, geophysical, and geotechnical results for the region into a Community Velocity Model or “CVM,” and validating intensive CVM computational results against recorded shaking data. The Western Basin & Range CVM Working Group convened in Reno in January and November of 2008, and has recommended that the USGS begin modest funding of a CVM construction and validation effort. Technical details are at [www.seismo.unr.edu/wbrcvm](http://www.seismo.unr.edu/wbrcvm).

WBRCVM construction and validation will lead over the next 5 years to more realistic Reno and Las Vegas hazard maps, as well as a more effective selection of time series for use in structural design. The working group welcomes the involvement of regional stakeholders members in many ways, among which are: 1) through contributions of geological, geophysical, and geotechnical data to the CVM from the Reno-Carson Urban Corridor (including Tahoe) and the Las Vegas Metropolitan Area (including Pahrump Valley); 2) by helping us define the desired products from the physics-based modeling needed by the engineering and emergency-response communities, and evaluating the effectiveness of our results; and 3) by helping us leverage the small amounts of USGS funds available, to appeal to a broad selection of possible sponsors for such work.

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### **TECHNICAL ABSTRACT**

Despite decades of effort it has been difficult for scientists to make complete assessments of the earthquake hazards faced by Nevada urban areas. The region is riddled with hundreds of active faults, few of them yielding much detail to researchers; earthquake waves will propagate from major fault zones through a geologically complex crust pocked with hundreds of basins large and small; and the urban basins bear few recordings of strong motions and had hardly been studied for their site conditions until recently. Nevada's potential hazard was brought into sharp focus during the spring of 2008 by the M6.0 Wells earthquake and the West Reno earthquake swarm, including the M5.0 Mogul event. Neither sequence occurred on a known fault; the downtown core of Wells was demolished; and surprisingly high ground motions were recorded in West Reno neighborhoods. These alarming developments give special impetus to the Western Basin and Range (WBR) Community Seismic Velocity Model (CVM) Working Group, which was formed with US Geological Survey support in January 2008. This broad-based group of scientists and engineers has the objective of creating a CVM to allow computation of expected shaking from scenario earthquakes affecting Nevada urban areas. One consensus the group identified was to follow the design of the Southern California Earthquake Center and Wasatch Front CVMs. However, WBRCVM development and applications are more challenging: the former CVMs address a few large basins that contain the main scenario faults, while in the WBR most of the hazard may originate on faults well outside the urban basins. So the WBRCVM must contain geological and geophysical information describing hundreds of basins at a range of scales, from regional crustal tomography down to local site conditions. Some areas have accurately measured properties, while others are little studied and must assume interpolated or projected values. The challenge for this group, with the very limited budgets available, is to produce a WBRCVM able to match any of the wealth of new recordings in scenario computations. Very simple 3D trials have been able to match the peak ground velocities recorded around the Wells earthquake, but not from the Mogul earthquake.

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**Keywords:** Site effects, Basin effects, Seismic modeling, Ground motions,  
Seismic zonation, Engineering seismology

### **Introduction**

Two workshops were convened under this grant: and initial workshop on Jan. 14-15, 2008 on the UNR Campus in Reno; and a followup workshop on Nov. 3, 2008 at the same location.

1. The initial workshop is described below by a white paper that includes summaries of presentations, a FY2009 NEHRP consensus priorities document, the workshop agenda, and a list of participants. This white paper was delivered to the USGS on July 23, 2008.
2. The followup workshop is described starting on page 30 by its agenda, a revised FY2010 NEHRP consensus priorities document delivered to the USGS in November 2008, and a list of participants. The NBMG has posted the priorities document at [http://www.nbmng.unr.edu/eq/WBRCVMW\\_priorities.pdf](http://www.nbmng.unr.edu/eq/WBRCVMW_priorities.pdf).
3. Additional materials summarize conference presentations on the Western Basin and Range CVM Working Group by J. Louie, including a copy of a peer-reviewed conference paper presented at the 2008 Society of Exploration Geophysicists Annual International Meeting in Las Vegas.

## **Nevada Great Basin Community Velocity Model Workshop**

*January 14-15, 2008 at the University of Nevada, Reno*

*Draft Summary by J. Louie, 7/23/08*

[www.seismo.unr.edu/gbcvm](http://www.seismo.unr.edu/gbcvm)

### **Objectives**

The Nevada Seismological Lab convened a 2-day workshop on creating a Nevada Great Basin Community Velocity Model (GBCVM), with generous support from the USGS NEHRP-NIW panel. The workshop was held in Reno on January 14 and 15, 2008.

The objectives of this workshop were two-fold:

1. To organize a Nevada community seismic-velocity modeling effort for the western Great Basin, contributing toward the goal of predicting earthquake ground motions in urban areas and other sensitive sites. The community model will address seismic velocities at the crustal, basin, and geotechnical scales; and should contribute directly toward an overall Great Basin Community Velocity Model.
2. To hear advice from national experts who have constructed CVMs for other areas including Utah, to assess what CVM features most affect predicted ground motions, and thus prioritize our needs for geological and seismic-velocity data.

### **Products**

- We developed at the workshop a succinct statement of research and data needs that was delivered to the NIW Coordinator, Mark Peterson, for inclusion in the FY09 USGS NEHRP-NIW announcement and RFP.
- This white paper, summarizing the discussions at the workshop. It is available at the [www.seismo.unr.edu/gbcvm](http://www.seismo.unr.edu/gbcvm) website to those writing NEHRP proposals.

### **Participant Support**

The USGS NEHRP-NIW panel kindly provided support for this workshop under grant no. 08HQGR0015, including travel reimbursements and/or stipends for out-of-town presenters, and refreshments and lunches during the discussions.

### **Workshop**

About 30 scientists, engineers, and stakeholders indicated their interest in the workshop. Twenty-one signed in but it is estimated that 25 attended. The sign-in list is below. On Monday, the workshop was a series of 20-minute presentations interspersed with breaks for open discussion. Tuesday was set aside for further open discussions, with specific goals:

1. What results do we need in a Nevada CVM for ground-motion prediction? Who will use the CVM, and how?
2. How do we obtain the necessary data and results? What methods are cost-effective enough to be funded? What collaborations are needed?
3. Write and order Nevada CVM priorities for the FY2009 NEHRP RFP.

The complete schedule is also below.

### **Summaries of the 18 Presentations:**

The following summaries are extracted directly from the presentations on line at the workshop web site, and other materials. *These materials are not the work of the convener, but belong to the authors named.* The convener takes full responsibility for any errors in transcription or paraphrasing that may be below.

John Louie, convener of the workshop from the Univ. of Nevada, Reno (UNR) introduced the goals and schedule of the workshop, the discussion topics, and the desired products. He acknowledged funding by the USGS NEHRP-NIW External Grants Program, and Regional Coordinator Mark Petersen. Beginning by setting the purpose of the CVM as predicting earthquake ground motions in urban areas and other sensitive sites, he described how the CVM will address seismic velocities at the crustal, basin, and geotechnical scales, and contribute directly toward an overall Great Basin Community Velocity Model. He described how the program was set up to hear from experts who have constructed CVMs in other areas, our need to assess what CVM features most affect predicted ground motions, and our objective of prioritizing our needs for geological and velocity data. But he also specified that this workshop and nascent working group would not assess seismic sources or faults, and suggested that activity would be more appropriate for the Great Basin Fault Working Group convened by C. dePolo to address. Finally Louie reviewed the specific Nevada priorities listed for FY2008 proposals that pertain to CVM efforts.

Louie continued with another presentation showing his graduate Michelle Heimgartner's thesis work assembling prior crustal-thickness data with new refraction results from the Sierra and Northern Nevada. The web site [www.seismo.unr.edu/geothermal](http://www.seismo.unr.edu/geothermal) provides full results. UNR students James Scott, Weston Thelen, and Christopher Lopez share credit for this work, along with Mark Coolbaugh of the Great Basin Center for Geothermal Energy (GBCGE) at UNR, and Satish Pullammanappallil of Optim Inc. The US DOE funded the work through the GBCGE. The goal of the project was to compile existing crustal information, establish a facility for long-range crustal refraction surveys at UNR, collect three new crustal refraction profiles across Northern Nevada and the northern and central Sierra Nevada, integrate new and prior results, create a regional crustal model that is available to others, and relate the crustal model to geologic processes. The three refraction profiles collected were the Northern Walker Lane (NWL) in 2002, the Idaho-Nevada-California (INC) transect in 2004, and the Northern Nevada – Utah (NNUT) transect in 2005. Results discussed in Heimgartner's 2007 M.S. thesis include: areas of extremely thin crust, approx. 20 km thick in northern Nevada; a crustal root beneath the northern and central Sierra Nevada; the observation of crustal thickness correlating with heat flow in the Great Basin; and analysis of how not all geophysical data sets agree (i.e., teleseismic vs. refraction/reflection). An early result given in a 2004 *Tectonophysics* paper by Louie et al. is that gold-mine-blast first arrivals are visible over 300 km from their sources on arrays of closely spaced PASSCAL Texan recorders. The INC transect achieved the first continuous crossing of the High Sierra crest with such an array. Louie then showed Heimgartner's crustal-thickness models for the central and northern Sierran root and the entire Great Basin, combining existing and new results, and showed the effect of selecting among disparate results by selecting for refraction and reflection

results rather than the teleseismic. The latest crustal thickness map of the western Great Basin includes a 100-km long area of 20-km crust southwest of Battle Mountain, Nevada, which is isolated but corroborated among several data sets. The map also shows a >50-km-thick crustal root under the northern and central Sierra Nevada.

John G. Anderson of UNR continued with a presentation on the need for accurate velocity models in Nevada. He began with a refresher on geodetic results across Nevada, and reviewed the work of his graduate Aasha Pancha (2006 *JGR*) to correlate geologic, geodetic, and seismic deformation rates across the province. Providing background on earthquake focal mechanisms and depth distribution, Anderson showed the locations of the region's population centers against the USGS hazard map. He explained that he would speak about problems specific to Reno and Las Vegas, and leave Salt Lake to the Utah representatives. He presented an animated view of ground motion recorded across the Japanese islands due to the 2004 Chuetsu M6.8 event, as an example of a data set that our CVM efforts should have an idealized goal of predicting. Examples of data sets from Nevada were shown; the records modeled by Pancha et al. (2008 *BSSA*) from Reno and shown in Su et al. (1998) for Las Vegas. Both of these data sets show prominent amplifications at higher frequencies related to the sedimentary basins below the urban areas. An animation from a SCEC TeraShake run shows striking basin and rupture-directivity effects on ground motions in Los Angeles. Anderson showed that regional-basin focusing and rupture directivity effects could be important factors in predicting ground motions in Reno. A prominent hazard for Las Vegas is the Death Valley fault system. In summary, seismic hazard applications for the CVM are: predicting basin response in Reno and Las Vegas; possible channeling of energy through basins such as from the Genoa Fault to Reno; possible directivity towards major cities such as the Garlock and other faults toward Las Vegas and from the Genoa/Mt. Rose and other faults toward Reno; and the testing of shaking models using precarious rocks.

David von Seggern of UNR described the results of joint seismic tomography and location inversion in the Reno/Carson City area, a project in collaboration with Leigh Preston and funded by USGS-NEHRP. The project's goals were to develop a tomographic velocity model in the Reno/Carson City area at kilometer scale to roughly 15 km depth; to relocate Nevada Seismological Lab (NSL) catalog seismicity jointly with tomographic imaging; to utilize cross-correlation times of P and S waves to constrain the relative hypocenters; and to compare imaging results with other available velocity results. Earthquakes from 2000 to 2006 were used, recorded on both analog and digital stations. Event magnitudes ranged from -1 to 5.4, and their depth distribution was trimodal, with blasts at the surface, most earthquakes at 5-12 km, and the deep 2003 swarm below north Tahoe between 24 and 28 km depth. Tomography inputs included >200,000 P and S travel times, >200,000 cross-correlation times, >14,000 earthquakes, 23 blasts, and 71 stations. The distribution of time residuals with respect to a 1-d model is Gaussian and centered at 0 sec. The Vp and Vp/Vs images derived had a horizontal resolution of 2 km (90 x 91 grid), and a vertical resolution of 1 km (42 depths, from -5 to 36 km, relative to MSL). To test the dependence on the starting they ran cases with various reasonable starting models and found no significant dependency of result on starting velocities. A checkerboard test, perturbing the final model, recomputing travel-times, and re-imaging



the velocity model, showed the regions resolved well and resolved poorly, generally quite good in the source region from -1 to 15 km below MSL. In the Vp/Vs as well as the Vp images the Reno basin is clear but not Tahoe or Carson Valley, perhaps due to the lack of basin stations except for in Reno. There are signs of the volcanic basin north of Lake Tahoe. Animations of N-S and E-W sections progressing through the image volume, and the  $6.0 \text{ km/s} < V_p < 6.5 \text{ km/s}$  isosurface show the reliability and coverage of the results. 3-d relocations show enhanced linear features compared to catalog locations. In summary, low velocities exist east of the Sierra Nevada at shallow depths, coinciding with known basins, and especially low in the Reno basin; the Sierra Nevada crest and westward have high velocities at shallow depth; and anomalously high Vp/Vs material apparently exists just above the 2003 deep (25-30 km) swarm of earthquakes under north Lake Tahoe.

Arthur Rodgers of Lawrence Livermore National Lab (LLNL) made a presentation on 3d models of the southern Great Basin and ground motion in Las Vegas. He reviewed projects over the last five years: the Las Vegas Ground Motion project supported by DOE/NNSA for test-site readiness, in collaboration with UNR (Louie, Anderson) and UNLV (Luke, Snelson, Taylor); and the Non-Proliferation Experiment Modeling project supported by DOE/NNSA BAA, and led by Steve Myers (LLNL), with participation of UNR (Smith, Preston). Future/Possible projects include EarthVision geologic models and the WPP anelastic wave propagation code. Rodgers described the study area, and the details available in Las Vegas Valley, and the legacy ground motion recordings in Las Vegas from NTS explosions. These data show amplification where the basin is deepest, but spatial coverage of the ground motion data is limited. The seismic spectral ratio amplifications are large, with peaks above 10 times. Site response shows strong variation within Las Vegas Valley, with amplifications strongest between 0.4-2.0 Hz, and in the central basin. For predicting ground motions for future events, the legacy ground motion data are valid from 0.2-5.0 Hz. 3D modeling can address the limitations of the legacy data. Spatial coverage is limited by model coverage, but low-frequencies can be easily modeled. The project built a 3D model of Las Vegas and southern Nevada, including NTS and Yucca Mountain. 3D modeling used Louie's Model Assembler model and Shawn Larsen's E3D code. LLNL (Jeff Wagoner) has further developed geologic models in the EarthVision system, particularly detailed near the NPE shot, with a target resolution of 60 m. LLNL's new WPP code reads octant-tree or "Etree" models in parallel, and an EarthVision-to-Etree tool makes these highly detailed models more accessible. Wanda Taylor (UNLV) and Jeff Wagoner (LLNL) are further refining geologic structure in Las Vegas from well-log interpretations. The Non-Proliferation Experiment (NPE) provides an excellent data set in the NTS area. Modeling the NPE with E3D improves our understanding of seismic waves generated by underground explosions in the presence of complex topography and geology. Current efforts include development of the WPP - anelastic wave propagation code. WPP is an elastic and anelastic finite difference code, 2nd order, with a node centered formulation, written in C++/C. WPP runs on Linux workstations/clusters & Mac OSX. It was born parallel (uses mpich) but can run on single processor. WPP is available for download: <http://www.llnl.gov/CASC/serpentine/software.html>, with a ~50 page user's guide and example input files. Current WPP features are: 3D P- and S-wave velocity and density



models; block, vfile (binary raster) and etree models; purely elastic (no attenuation); handles the acoustic case, where rigidity=0; absorbing (Clayton and Enquist) boundary conditions; free surface boundary conditions; models an arbitrary number of sources including point moment tensor & force, with many source-time (moment) functions available; writes time-series of motion as SAC files and 2D and 3D images; mesh refinement. Coming soon are free surface topography and embedded boundaries.

Barbara Luke of UNLV presented on shear wave velocity profiling in Las Vegas Valley. The UNLV Engineering Geophysics Laboratory maintains a shallow velocity database for Las Vegas basin at [http://www.ce.unlv.edu/egl/lv\\_archives/](http://www.ce.unlv.edu/egl/lv_archives/). In collaboration with Helena Murvosh of Stanley Consultants Inc., Wanda Taylor of UNLV, Eduardo Gonzalez of UNLV, Catherine Snelson of New Mexico Tech, Jeff Wagoner of LLNL, and Qihong Su of UNLV, Luke presented the following abstract at the 2008 Geol. Soc. Amer. Cordilleran/Rocky Mtn. Sections meeting in Las Vegas that effectively summarized her workshop presentation: "In the event of a major earthquake near Las Vegas, weak-ground-motion data have shown that the intensity and spectral content of ground shaking will be variable across the Las Vegas Basin. The Basin, which covers approximately 1600 square kilometers in surface area, is home to about 2 million people. A preliminary microzonation, based on predominant sediment type in the upper 30 m and validated using weak ground motion measurements, has identified two zones. One zone encompasses the central to eastern portion of the Basin where fine-grained sediments predominate, and the other encompasses the western portion of the Basin and around the Basin margins where gravels predominate. Because shear wave velocity is a key parameter in defining the response of a sediment column to dynamic input, the microzonation effort is being advanced by expanding the velocity map of the Basin, in terms of both coverage and detail. Emphasis is on characterizing velocities and their variation using surface waves. Through use of a "minivib" vibroseis and passive-source methods, dozens of detailed, one-dimensional profiles are being resolved, in some cases to depths of 100 m or more. The database is supplemented with 160 simpler shear wave velocity profiles that were collected for development purposes and filed in public records. When coupled with deep shear-wave velocity data collected using single-station group-wave velocity measurements, the data will facilitate generation of a three-dimensional shear-wave velocity map of the Basin. Intelligent interpolation of velocity data will account for sediment type, the presence of faults that cut the sediments, and possibly alluvial-fan source materials. In addition to the shear wave velocity of the shallow sediments, other key factors influencing ground-surface shaking in the Basin are multi-dimensional basin-edge interference effects, near-fault effects and the dynamic response of the Basin's deeper sediments. Supplementary to the velocity maps, analyses are planned to investigate the impacts of these variables on sediment response. Amplification factors developed through this process can be applied, along with the characteristics of the earthquake-producing faults, to build seismic hazard maps for use in urban planning."

Aasha Pancha of UNR presented on the need for an accurate Reno velocity model to understand amplification in the Reno basin. For Nevada this basin is well characterized with over a dozen ANSS stations in the basin, a recent gravity model for Quaternary and Tertiary sediment thickness, and (before February 2008) two M4.4+ earthquakes

recorded from west of the basin. The recordings show clear basin effects of amplification and extended durations of shaking. The recordings were modeled from 0.2 to 0.6 Hz using both 1-D methods and 3-d methods, specifically Louie's MA-CME including a basin-thickness model and the results of geotechnical measurements and Larsen's E3D finite-difference code with a grid spaced at 0.25 km. Comparisons against recorded seismograms show that the 3-D modeling is necessary; 1-D modeling does not reproduce recorded amplitudes or durations. Further study of recordings of 21 earthquakes and their response spectra within the Reno basin shows a high degree of spatial variation of amplification within the basin, as well as rapid variations in response with frequency. Distance-normalized amplifications have an insignificant correlation with basin thickness, but arrival-time residuals do correlate with thickness and with spectral amplification averaged from 0.2-0.6 Hz. Amplifications correlate strongly with Vs30 and Vs100. At some stations an azimuthal dependence of amplification spectra can be seen. In sum, there is good agreement between amplitudes of the data and of the 3-D simulation; the 3-D modeling with E3D and MA-CME models durations well and may anticipate later arrivals; 3-D basin effects are important and required to correctly model Reno recordings; and the basin-structure and velocity models need refinement.

Chris Henry of UNR presented the three-dimensional geologic complexity of the Truckee Meadows basin from geologic mapping. He began with a new geologic and fault map of the basin and the surrounding mountains. With an E-W section through the Huffaker Hills he proposed the hypothesis that the basin may be composed of two asymmetric basins developed along west-dipping faults. A new 7.7 Ma date on the Huffaker Hills Tertiary volcanics suggests that 13-8 Ma basin sediments may underlie the Hills. This is a complication in the structure of the basin not at all suggested in Abbot and Louie's (2000) gravity analysis, but not necessarily in conflict with their data. It suggests structural complications in the basin edges that could have significant effects wave propagation and amplification. Currently it is unknown whether there is a possibility of basin sediments similarly underlying any of the other many volcanic hills at the edges of the Truckee Meadows basin. It is further rather difficult to test Abbot and Louie's proposed separation in their Reno cross section of the active extension of the Mt. Rose fault from the Tertiary faults against which the basins developed. Much further work is needed on the Tertiary to Quaternary to Recent tectonic development of the basin, and on the changes with time of tectonic styles that have been proposed. With a bit of a wider regional view, clues to the basin's history may be found in other Tertiary to Recent basins such as Boca, Truckee, Tahoe, Washoe Valley, and fragments of basins in the Virginia Range. Seismicity maps and focal mechanisms will contribute critically toward such analyses. Work on the Steamboat Hills, funded for geothermal purposes, will also play an important role.

Lee Liberty of Boise State presented a case study for building a CVM, from geophysical characterization of the Hot Creek Valley, central Nevada. The DOE has funded several investigations of this basin in Nye County, which is still reserved as the Central Nevada Test Site. An underground nuclear test conducted below the Valley motivated extensive seismic reflection and refraction studies, with the goal of understanding the valley's structure and stratigraphy sufficiently well to model the transport of radioactive

contaminants in the valley's aquifer. Liberty showed how a carefully planned set of surveys and appropriate processing techniques at the 2-km scale could reveal the stratigraphic and structural details of the basin.

Morgan Moschetti of the Univ. of Colorado, Boulder presented on the application of empirical Green's functions for the construction and validation of the GBCVM. His co-authors on this presentation were Michael Ritzwoller of Colorado, and Arthur Rodgers and Anders Petersson of LLNL. Beginning with a review of ambient noise processing for EGFs, he showed example Rayleigh group-velocity spectra between station pairs from 5 s to 30 s period. Over 51,000 station pairs are developed by the 477 stations of the current US Array deployment, leading to complete surface-wave group and phase velocity results over the Western US west of longitude 111°W. Results are posted at <http://ciei.colorado.edu/~morganm>. From the phase-velocity dispersion curves a neighbourhood algorithm to defines an ensemble of acceptable models. The model resulting from this 3-D inversion shows crustal thickness >42 km in the northern Sierra, about 40 km in the central and southern Sierra, and 30 km or less in parts of northern Nevada. Further interpretations can be made from map slices of the model as shallow as 0-10 km. Comparison of Rayleigh waveforms in the EGFs and synthetics provide validation of the USGS Bay Area 3-D Velocity Model over 130 common paths. Empirical Green's functions within and across Nevada for comparison and inversion. From EGFs, shear-wave velocities across Nevada have been developed for background values and for model/inversion constraint. Comparison of EGF and synthetic waveforms allows for validation and assimilation of models. Improved data coverage from higher density arrays recorded in the past or future will allow constraints to be more detailed.

John Louie of UNR presented on The MA-CME modeling environment and initial scenario ground-motion computations for Reno and Las Vegas. Leif Preston (formerly UNR, now Sandia Labs), Shawn Larsen of LLNL, and UNR undergraduates Liz Lenox, Rei Arai, and Amr Wakwak in the Dept. Geological Sciences and Engineering also contributed. Model Assembler is a code to stitch together existing regional geophysical and geological data sets at multiple scales. It generates the multi-gigabyte input grids for 3-d seismic modeling routines such as Larsen's E3D. The ModelAssembler Community Modeling Environment (MA-CME) provides a graphical user interface for setting up MA/E3D ".in" files, as well as tutorial help to a successful setup. Data sets, stations, and grids are all defined with geographic lat/lon. MA-CME provides easy configuration of problems at all scales and computational difficulties- from 10 Mb to 100 Gb. After setup, a "portal pack" is downloaded to a cluster and run. MA-CME is open source, with everything available from: [www.seismo.unr.edu/ma](http://www.seismo.unr.edu/ma). MA-CME's current limits include: flat earth; no topography; 1-D variations within basins & bedrock; and sources and stations must be within the same grid. In the Basin and Range, 3-d basins are represented by four datasets, not well stitched together: 1) a geologic map with basin depths assumed from bedrock proximity, in California; Jachens et al. USGS basin gravity inversions for the Basin & Range, including sedimentary as well as Tertiary volcanic basins; Abbott & Louie's (2000) Reno basin gravity study, and the Langenheim et al. Las Vegas model from gravity, refraction, a few deep wells. Trial modeling at 0.3 Hz was shows for three scenario faults: a Genoa system M7.5 rupture 80-km-long north into Reno; a Frenchman

Mtn. M5.0 rupture in Las Vegas Val.; and two 80-km-long, M7.5 Northern Death Valley – Furnace Creek scenarios, one rupturing away and one toward Las Vegas. In the Reno area MA-CME included geotechnical data sets, the Scott et al. (2004) Vs30 transect, and Pancha measurements at ANSS stations. MA performs a “Quadrant” interpolation between scattered measurements, respecting the geologic map. Vs30=500 m/s was assumed on sediment; 760 m/s (white and cyan) on rock. The Genoa scenario included an Olsen and Day Q model; the results shows an extreme directivity effect and >15 cm/s motions in the west Reno basin. The greatest shaking was not correlated with basin depth, despite Tahoe being artificially deep in this model. Dataset boundaries are not interfering with these conclusions. In Las Vegas Valley MA-CME used the Langenheim et al. model from gravity, refraction, and a few deep wells for basin thickness; and the Scott et al. (2006) Vs30 model from 1100+ wells, and 79 Vs profiles (thanks to W. Taylor and B. Luke of UNLV & J. Wagoner of LLNL) for the geotechnical input. For the Frenchman Mtn. scenario basin-floor structure appears to contain the areas of greatest shaking. For the Death Valley scenarios, Jachens Basin & Range gravity inversions for sedimentary & volcanic basins show the Timber Mtn. caldera & radiating rifts are up to 8 km deep. The detailed models for Las Vegas basin thicknesses and geotechnical velocities are integrated into the regional 3-d model. The two M7.5 rupture scenarios have very different effects, though they are on the same fault. For rupture toward the city, PGV >1 cm/s in parts of the Valley. The wave-propagation animations can be downloaded in cell-phone format from [www.seismo.unr.edu/ma/](http://www.seismo.unr.edu/ma/) . There is clear directivity in this long-period simulation. Basins between DV and LVV are spreading the directivity effect to wider angles from the fault strike than would be expected in a half-space. At long periods, 0.3 Hz, the MA-CME and E3D modeling path is showing huge uncertainties in expected PGV.

Jack Odum of the USGS, Boulder, presented on the USGS and the development of the Nevada Great Basin Community Velocity Model. The agency’s objectives with a Nevada CVM are: to help Coordinate efforts between UNLV, UNR, USGS, others, to develop a CVM patterned after Wasatch CVM effort; to make the CVM available to the public when completed; and to develop urban seismic hazard maps for the Reno and Las Vegas metropolitan areas. The Seattle 3D Vs Model used in Seattle urban seismic hazard maps provides another prototype, and is available as USGS Open-File Report 2007-1175 at <http://pubs.usgs.gov/of/2007/1175> . The Seattle urban seismic hazard mapping effort began with the 2002 National Seismic Hazard Map plus NEHRP Amplification factors based on Vs30. With the 3D Vs model, a new map was developed incorporating ground motion simulation results (basin effects, rupture directivity, and nonlinear soil response at soft-soil sites). Information important in developing community velocity models (not inclusive and area dependent) is regional geology (including basin Quaternary units and all active faults), realistic basin geometry (from gravity, seismic tomography, boreholes, etc.), geotechnical data (borehole), and geophysical data (Vs, Vp, density, attenuation, etc.). Possible steps for the Nevada research community to reach similar objectives are to coordinate the compilation of all existing relevant data (how much data is there?), develop models with existing data (using searchable code, e.g., Wasatch CVM, ModelAssembler, 3rd party 3D software), model validation (determine what additional data is needed, where is it most needed), and to acquire new data for incorporation into

the models. Funding for such efforts is dependent on funding levels from Congress. Historically, ~\$120k has been available for these types of efforts every year in National/Intermountain West panels, translating into ~1-2 proposals funded annually. The USGS has historically collaborated on data acquisition with internal funding and anticipates doing so in Nevada, if needed. Odum continued with examples from the USGS effort to help build the Wasatch Front CVM, showing the collection seismic reflection/refraction data and their interpretation for the depths of principal impedance contrasts.

Harold Magistrale of SDSU presented progress on the Wasatch Front CVM. His co-authors in this effort are Kim Olsen of SDSU and Jim Pechmann of UUS. The Wasatch CVM is a rule based seismic velocity model with several steps in its development: 1) compile geologic and geophysical information (e.g., stratigraphy, oil well sonic logs, tomography results); 2) define reference surfaces (or other objects e.g., lithologic contacts [isoage surface], isovelocity surface, tomography model nodes); 3) compare point of interest to objects and interpolate properties (e.g., interpolation of age between surfaces, interpolation of velocity between tomography nodes); and 4) apply rules to get velocity (or other property) at point of interest (e.g., linear gradient between isovelocity surfaces, Faust's rule [velocity-age-depth relation  $V_p = k(da)^{1/6}$ ]). The area of the CVM focuses on the urban Salt Lake City region, about 120 km E-W and 180 km N-S, and incorporating the Weber, Salt Lake, and Utah basins among others. Principal elements of the CVM are soil classes, geotechnical boreholes, basin sediment interfaces (R1, R2, R3 in Salt Lake Valley; and R1, basement (gravity, wells, seismics) in other basins), deep boreholes (seismic velocities), crustal tomography, and Moho depths. Crustal  $V_p$  tomography comes from Loeb and Pechman (1987) and Lynch (1999), set into a standard 1D model. Basin-thickness models come from deep wells, Mabey (1992), Bashore (1982), McNeil and Smith (1992), Mattick (1970), and geologic maps. Much of the work in assembling the model is in integrating R3 depths from existing maps and networks of seismic surveys; much of this work is done by hand with educated guesses for interpolation and data selection. In many basins only the R3 depth is available, so an R2/R3 correlation study was performed on data shown by Radkins (1990) for Salt Lake Valley. Despite the scatter there is enough correlation for R2 to be estimated in nearby basins at 0.36 of R3, yielding an R2 model of consistent coverage along the Front. R1 depths come from Solomon et al. (2004) and Wong et al. (2002); and an R1/R2 correlation allows R1 depth estimation outside the coverage of these data sets. The model overall is parameterized similarly to the SCEC CVMs, with velocity gradients between surfaces according to Faust's rule:  $V_p = k(da)^{1/6}$ . Deep bores with  $V_p$  logs can test the predictions of this model, and their logs are inserted in their locations. Radkins et al. (1989) show the logs, in which the R1 and R2 impedance contrasts are readily identified. Model predictions are good. For density, Ludwig, Nafe, and Drake (1970) compare empirical relations to  $V_p$ ; in Los Angeles the SCEC CVM version 3 was updated to version 4 with geotechnical data showing  $V_p$  as low as 300 m/s, allowing a linear  $V_p$ /density relation to be anchored at 1.8 g/cm<sup>3</sup> at  $V_p=0$ . Geotechnical velocities were estimated everywhere from geologic units, such as from Ashland (2001; 2004). In Oct 2006 McDonald showed an extensive set of geotech measurements. The profiles, as deep as 85 m, were averaged for each mapped unit, within each basin.  $V_p$  is estimated from the  $V_s$  measurements using Castagna et al.

(1985):  $V_p \text{ (km/s)} = 1.16V_s + 1.36$ , with  $1.5 < V_p < 4.5 \text{ km/s}$ , from Brocher (2005). Measured profiles adjust basin-averaged profiles within a 2 km radius. Shallow  $V_s$  outside basins is still rather high, above 1500 m/s at 30 m depth. Initial validation synthetics show excellent timing of initial phases, though long surface-wave durations are not represented.

Robert Sydnor, an independent engineering geologist, presented applications of shear-wave velocity to the Building Code. The applications in engineering geology and applied geophysics include: classification of the geologic subgrade (Class B, C, D); the default method for ground motion (coefficients  $F_a$ ,  $F_v$ ); soil-structure interaction (coefficient  $V_{so}$ ); rippability of rock (deeply? weathered granitic rock); liquefaction analysis ( $V_s$  proxy for  $N_1(60)$ - see: Andrus & Stokoe (2000)); remediation of liquefaction (acceptance criteria for improved ground); reclassify the subgrade after remediation (from D to C?); complicated geologic subgrade (mine tailings & landfills); reconnaissance for drilling program (borehole spacing & depth). Attention should be paid to conceptual map-scales for shear-wave velocity. Regional or statewide maps can be combined with regional fault models and PSHA for maps of strong ground-motion for statewide seismic-safety planning. City & county scale maps from regional seismic surveys and earthquake studies can be compiled by seismologists, engineering geologists, and petroleum geophysicists (proprietary data). Project-level specific work is highly detailed; combined with subsurface exploration data such maps assist building code applications for structural engineers (earthquake ground-motion design and soil-structure interaction). Regional map making has limited funding from Congressional appropriations via NEHRP, NSF, SCEC, USGS, academia; such funds are awarded to academia, state geological surveys, U.S. Geological Survey, national labs, etc. City & County scale maps have the greatest need for funding, for regional seismic surveys and earthquake studies funded by NEHRP grants via USGS, NSF, SCEC, and the California Earthquake Authority. Consulting geotech firms, insurance actuaries, county & city engineers & planners are important stakeholders in these efforts. At the project-level specific work scale the high costs for building permits motivates subsurface exploration for specific shear-wave measurements (crosshole, seismic cone, ReMi, hammer-seismics), funded by bank loans via owners of large structures. These proprietary funds bring new robust software & new geophysical equipment by high-technology firms & drilling companies resulting in reliable shear-wave velocity at lower cost. Predicaments, weaknesses, and drawbacks with the Building Code include the fact that it is expensive to purchase (hundreds of dollars); has limited availability (not in most public libraries; not in many university libraries; many small geotechnical consulting firms have no copy of current code); it is tedious to read and has an obtuse & dry format, unfriendly for beginners & students, 95% does not apply to seismology, geology, or geotechnical engineering, and there are no flow-charts, no logic trees, no markov chains to explain tedious pathway; and the many collateral references to ASCE Standard 7-05 (have to purchase yet another expensive book). The strengths and Benefits of the 2006 International Building Code & 2007 California Building Code include: that it contains modern seismology concepts; eliminates old seismic zones 3 & 4 to focus on “real” ground-motion; retains emphasis on average shear-wave velocity ( $V_{s30m}$ ), introduces the term Maximum Considered Earthquake; contains collateral references to ASCE Standard 7-05, with commentary not found in 2006 IBC written by

an excellent seismology committee; and allows for site-specific calculation of ground-motion. A significant change in view is needed by structural engineers designing large structures on heterogeneous parcels where  $V_{s30}$  may change significantly across the project's footprint. ASTM standard test methods addressing  $V_{s30}$  include D-4428M-07 for cross-hole seismic testing, D-6429-99 (2006) "Guide for Selecting Surface Geophysical Methods," and D-7128-05 on the shallow seismic-reflection method. A new ASTM Standard is needed for the ReMi method. Regarding the Code's call for  $V_{s30}$  measurements, there is no geophysical basis for the "convenient" depth of 100 feet. Modeling of strong ground-motion, plus insights from existing downhole strong-motion accelerometer arrays might yield a different depth than 100 feet. Most boreholes in alluvium are typically  $\approx 50$  feet for 4 reasons: typical limits of liquefaction are  $\approx 50$  ft;  $< 50$  foot limit for Boussinesq pressure bulb for typical 1 to 2-story buildings; the drill stem on most drilling rigs is  $\approx 65$  feet; and drilling costs— the practical efficiency of two 50-foot boreholes vs. one 100-ft. A suggestion for applied research is to develop a regional map of the Great Basin showing basement contours. A historic example from California is Smith (1964) U.S. Geological Survey Oil & Gas Map OM-215, prepared as a petroleum exploration map, and has useful comprehensive statewide coverage. How do deep sedimentary basins amplify earthquake ground motion? OM-215 is 44 years old, but the historic insights may be a good example for the Great Basin.

Chris Wills of the Calif. Geologic Survey presented on preparing maps of  $V_{s30}$  based on geologic maps of California. His subtitle was "Why geologic maps don't correlate with  $V_{s30}$ ." As early as 1907 Soule recognized that "The destruction wrought by the earthquake amounted to little or nothing in well-built structures resting upon solid rock and, all other things being equal, increased in proportion to the depth and incoherent quality of the foundation soil," confirmed by 1989 Loma Prieta recordings at Treasure Island in San Francisco Bay. Wills and Silva assembled a database, partly proprietary, with 649 downhole, 118 CXW, 88 suspension-logger, and about 200 other  $V_s$  measurements statewide. The CXW results do not correlate well with other nearby measurements, averaging hundreds of m/s higher. Histograms of  $V_{s30}$  results in a few simplified geologic units show clear peaks but large ranges. The 2000 statewide classification values show good correlations to PGA and spectral amplifications from 0.3 s to 3.0 s periods. The statewide class map was integrated with the USGS probabilistic hazard map for a 2003 shaking potential map. Yet, Wills quoted from several sources as early as Steidl (2000) on the inability of geologic maps to predict  $V_{s30}$ . Current efforts begin with the physical property units of Tinsley and Fumal (1985) and conduct mapping specifically with hardness and  $V_{s30}$  in mind; rather than geologic age, process, or provenance. Sub-dividing the young alluvium when soils maps and geomorphic maps don't correlate with  $V_{s30}$  might take two paths: build a detailed 3-d map based on subsurface  $V_s$  data; or find an effective proxy for  $V_{s30}$  in young alluvium. Distance from rock correlates with  $V_{s30}$  in young alluvium. An example is the division of Qal into fine, deep, thin, coarse, deep Imperial Valley, and thin west LA subunits. The  $V_{s30}$  histograms for these units are more predictive than for geologic units. A statewide map draft has been prepared using the physical property units. Predicted  $V_{s30}$  values are now closer to measurements. An example of increasing scale of mapping in Los Angeles indicated the detail needed to match the degree of lateral heterogeneity observed. Preliminary maps



also show the classification of young alluvium based on distance from rock. Topographic slope also correlates with Vs30 in young alluvium, as shown by Thelen et al. (2006) and Wald and Allen (2007). Three simplified slope ranges or categories can give a reasonable Vs30 prediction. Another preliminary Vs30 map of Los Angeles uses slope to subdivide the young alluvium. In sum, geologic maps show areas underlain by different geologic units that can have different physical properties. They can be generalized to maps of Vs30. Detailed sub-units of young alluvium commonly do not have distinct Vs30 – maps that subdivide young alluvium typically only have information about the upper 3 – 5 m. Both distance from rock and surface slope appear to be effective proxies for grain size in young alluvium – they can be used to make more detailed maps of Vs30. Finally, Vs30 measurements of crystalline bedrock in southern California appear to be problematic. Downhole measurements have a large mean (748 m/s) and standard deviation, while SASW measurements in bedrock have a low average (510 m/s). ReMi measurements in rock are intermediate, averaging 622 m/s, with a lower variance. Weathering of fractured rock produces fine-scaled heterogeneity, perhaps affecting the measurement techniques.

Arthur Rodgers of LLNL presented on the 1906 modeling effort, and lessons learned. Much of his presentation referenced material presented at the Dec. 2007 AGU meeting S21A-0235, on “3D structure effects on local and near-regional seismic wave propagation in the San Francisco Bay Area” in a presentation by Kim, A., Dreger, D., and Larsen, S.: “In this study we performed 3D waveform modeling of 10 small to moderate events (Mw 4.1-5.0) in the San Francisco Bay Area using the USGS SF06 3D velocity model (Brocher et al., 2005; Jachens et al., 2005). In the simulations we assumed the source parameters reported in the Berkeley Seismological Laboratory (BSL) Moment Tensor Catalog. Broadband seismic data from the Berkeley Digital Seismic Network (BDSN), and strong motion data from the USGS and the California Geologic Survey California strong motion arrays were used in the analysis. We analyzed and modeled the data in three frequency bands, namely 0.03-0.15 Hz, 0.1-0.25 Hz, and 0.1-0.5Hz. Preliminary waveform modeling shows that the USGS SF06 model predicts many important features of observed seismograms including bodywave arrival times, and peak ground velocity. On the other hand, as reported by Rodgers et al. (2007), the model produces late arriving surface waves. While peak ground velocity is generally well modeled there are paths that have significant amplitude mismatches and also poor waveform fit to sedimentary basin generated surface waves. We are identifying which paths need additional waveform modeling in order to further calibrate the 3D structure. We will present the bodywave and surface wave arrival time, and peak ground velocity correlations as well as forward modeling results for the problematic paths. References Brocher, T. M., (2005). Empirical relations between elastic wave speeds and density in the Earth's crust, *Bull. Seism. Soc. Am.*, 95 No. 6, 2081-2092. Jachens, R., R. Simpson, R. Graymer, C. Wentworth, T. Brocher (2006). Three-dimensional geologic map of northern and central California: A basic model for supporting ground motion simulation and other predictive modeling, 2006 SSA meeting abstract, *Seism. Res. Lett.*, 77, No.2, p 270. Rodgers, A., A. Petersson, S. Nilsson, B Sjogreen, K. McCandless (2007). Broadband waveform modeling of moderate earthquakes in the San Francisco Bay Area and preliminary assessment of the USGS 3D seismic velocity model, submitted *Bull. Seism. Soc. Am.* <http://seismo.berkeley.edu/~ahyi/>”

Louie briefly gave a presentation sent by G. Randy Keller of the Univ. of Oklahoma, who was not able to attend the meeting, on the Open Earth Framework (OEF) and building 3-d models via integration of geological and geophysical data. Keller thanks colleagues such as Eva Rumpfhuber, Aaron Velasco, Kate Miller, George Zandt, Matt Averill, John Hole, Matt Fouch, David James, and Harold Gurolla for their discussions of the subject. The OEF project has been funded by NSF under GEON. Keller begins by asking how might we go about constructing the desired 3-D model. Obviously if we are to determine  $V_p$ ,  $V_s$ , density, magnetic properties, electrical properties, anisotropy, attenuation ( $Q$ ), temperature, etc., we must use a highly integrated approach that takes advantage of all the geological and geophysical constraints available. In most cases, seismology has the potential of providing the greatest resolution, but it is the mostly costly approach and many diverse techniques are available. Thus, an integration scheme for seismic results is an important first step in any study. The best starting point would usually be 3-D tomography. In several recent experiments, crustal models have been constructed from controlled source data and used to constrain body wave and/or surface wave tomography of the upper mantle. One could also imagine using joint inversion for earthquake hypocenters and a velocity model as part of this process. Integration of geologic and geophysical data from mantle to near-surface scales is essential. Keller gives an example of joint inversion of different types of seismic data by Matt Averill and Tiffni Bond in the Trans-European Suture Zone. Construction of 3-D volumes with as many physical properties as possible assigned to each volume element is the ultimate goal. 3-D modeling is a reality for many types of data and situations, but integration and iteration remain as major challenges. The OEF group has been working with groundwater colleagues to create a 3-D data model within a GIS framework. They propose an integration scheme for geophysical data, with separate paths each constraining  $V_p$ ,  $V_s$ , and the  $V_p/V_s$  ratio, feeding into a smooth velocity model into which discontinuities are integrated, with the result checked against gravity data. They propose one work from the surface down because we have the most data there, and the near surface always has a potential to mask deeper features. Establish a region context, and then model the data set with the highest spatial resolution first. Start with accepted relationships between physical properties and then look for anomalies. Several groups are working on related problems and have surprisingly similar visions of what they need. However, they all seem to face some common challenges (model construction, editing, integration). This effort is different in that the gap between concept and implementation is very large and requires a large amount of software interfacing and development.

No time was left on Monday for Louie to speak on CVM efforts in Wellington, New Zealand. That work is a collaboration between R. Benites, G. McVerry, & W. R. Stephenson of GNS Science, S. Pullammanappallil & B. Honjas of Optim Inc., and Anna Kaiser, of VUW. Support came from Fulbright New Zealand and M. Henderson, M. Savage, & T. Stern of Victoria Univ. SES; and S. Harder & G. Kaip, of Univ. of Texas El Paso. Benites & Olsen (2005) created a 3-d grid at 40-m spacing to cover the Wellington fault and nearby basins. Louie hopes to promote and extend their model, and make the model computations easier and more flexible. The problem of many small basins is similar to the many basins surrounding Reno and Las Vegas. Benites and Olsen's model

was assembled from “all available geological and geophysical (borehole, bathymetry, gravity, and seismic) data, down to about 800-m depth.” Ground motions were computed with Olsen’s staggered-grid viscoelastic finite-difference code up to 1.5 Hz. The low-frequency computed motions are mainly dependent on fault geometry, rupture model, basin-floor geometry, and site velocities. Louie adapted the model into MA-CME for Larsen’s E3D finite-difference code, creating a Wellington Community Seismic Modeling Environment for extensions to models, addition of scenarios, and grids at multiple scales. MA-CME can easily generate grids for local (Parkway) and regional (Wairarapa) scenarios. ModelAssembler’s rule-based gridding combines into the CME: Benites & Olsen’s bedrock depth map (Z1.5, depth to  $V_s=1.5$  km/s); and their simple Vs30 map, 1.5 km/s in bedrock, 0.175 km/s in basins. Computed ground motions at 0.5 Hz depend more on Vs30 than Z1.5. Louie and Kaiser measured 46 sites for Vs30, finding that most Vs30 measurements are not as low or as high as the Benites & Olsen model predicts. ModelAssembler allows changes to the rules that govern modeling and gridding. Default Vs30 values for basin and rock sites were altered to better fit the measurements. Average rock Vs30=660 m/s, and average basin Vs30=250 m/s. With the new geotechnical input a 75% greater max. horiz. ground velocity compared to the original Benites and Olsen volume was modeled— despite the higher Vs30 in basins for the revised model. For a regional scenario enabled by MA-CME, the detailed Benites & Olsen model was set into a basin-thickness map from gravity or geologic maps. In sum, Benites & Olsen’s WnLH model has been adapted into a flexible CME for Wellington. Characterization of 21 GM recording sites in Wellington – Lower Hutt allowed re-calibration of the 3-d model. Including a slow surface layer on bedrock increases shaking in basins. Gravity and geology allow CME extension to larger regions.

### **Summary of Tuesday’s Discussions:**

The group began by considering the applicable FY08 NEHRP external-program priorities posted by the NBMG and included in the FY08 RFP:

- Improve and validate 3D velocity models needed for waveform modeling of the effects of basin- and near-surface-geology:
  - For Reno-Carson City, and Las Vegas
  - Using a variety of techniques including Vs30, tomography, inversion of seismograms, correlations with incorporation of geology, etc.
  - Incorporate results into the Community Velocity Model
- Test the sensitivity of shaking to velocity structure at various scales
  - As a guide to identifying those parts of the velocity model most in need of further study
- Use ANSS data in Reno/Carson, and Las Vegas
  - To find empirical site response, validate predictions of 3D velocity models, and improve ground motion prediction approaches.
- Prepare scenario ground motion models based on waveform modeling
  - For earthquakes on major faults affecting Reno/Carson and Las Vegas.

*Consensus on the geographic areas of interest of a Nevada CVM for ground-motion prediction—* Discussion initiated on defining the areas of interest for predicting ground

motions in the Reno/Carson and Las Vegas metropolises. A region that includes the target Nevada urban areas and the likely source areas such as the Eastern California Shear Zone in the Mojave Desert and the Walker Lane to its north end is best termed the Western Great Basin. For continuity with the Wasatch Front CVM, some aspects of a Nevada CVM will continue eastward from the Central Nevada Seismic Zone across the state line into Utah. Thus the group decided the most appropriate name for the CVM would be the “Western Basin and Range CVM” (WBRCVM). Unlike the Wasatch Front CVM as presented by Magistrale, the WBRCVM will have two levels of detail: a rough level of regional information, and a detailed level of information around the two Nevada urban areas. This scheme bears some similarities to Magistrale’s SCEC CVM version 4, which has additional levels of detail for the Los Angeles–Ventura and the Coachella–Imperial Valley basins.

Discussion then turned to the definition of the urban areas where the higher level of detail would be sought. In Nevada, urban development has gone beyond the Truckee Meadows basin and the Las Vegas Valley basin, with significant populations, facilities, and transportation corridors now occupying the Tahoe, Eagle Valley (Carson City), and Carson Valley basins in northern Nevada; and the Pahrump Valley basin in southern Nevada. Thus the two urban areas of interest are defined by this workshop as the “Reno–Carson Urban Corridor including Lake Tahoe,” and the “Las Vegas Metropolitan Area including Pahrump Valley.”

*Consensus on results needed for the entire region of the WBRCVM*– In the following lists of needs for data to include in the WBRCVM, an item designated “0.” would be an existing data set that requires adaptation to the WBRCVM; “1.” denotes an urgent data need that is included among the priorities suggested for the FY09 NEHRP NIW RFP; and “2.” denotes the next priority of critical data needs that could be included in a later RFP, to be funded for the purpose of improving and testing the initial WBRCVM that we hope to have before FY2011.

***WBRCVM regional data needs:***

0. Existing P-wave tomography for crustal and upper-mantle velocity variations- start w/ Hearn’s Pg work- then add VonSeggern and Preston’s Reno-region tomography; Biasi’s upper-mantle tomography; Smith, Preston, Myers, Wagoner So. Nevada detailed upper-crustal model.
0. A crustal Vs model exists now from the Transportable Array empirical Green’s functions (EGFs, by Moschetti and Ritzwoller).
0. Sedimentary and volcanic basin geometries across the region are available from Saltus & Jachens (1995) gravity inversion.
0. A geotechnical layer can be assumed from geological maps and rock vs. soil averages of Vs30 measurements (Scott et al. 2006 suggested rock Vs30 = 760 m/s and soil Vs30 = 500 m/s for the Las Vegas area), or perhaps from the Wald & Allen (2007) USGS Vs30 predictions from topographic slope for ShakeMap.
2. Check tomographic results against gravity such as the Saltus & Jachens (1995) database.
2. Develop improved projections for geotechnical velocities; Wills proposed to scope out application of Wills & Clahan projections based on hazard mapping and bedrock

proximity for the region. Databases developed for the MX Missile project should have excellent regional coverage and need to be dug out and inspected.

2. Catalog of fault dips (add to Qfaults?), Geology (structure and stratigraphy) of basin edges- possible collaboration with DOE-geothermal efforts?
2. Rework of Jachens regional basin gravity with better fault dips

***Reno/Carson City Urban Corridor (incl. Tahoe) data needs:***

0. Adopt Reno region P-S tomography from VonSeggern and Preston.
0. Include results of deep basin (>100 m) Vs results from Louie, Tibuleac, Preston (project currently funded by NIW FY'08).
0. Create a geotechnical layer by interpolation between Scott et al. (2004) and Pancha et al. (2007) measurements.
0. Assemble existing sections through Reno and Carson Valley (input from Cashman, Henry).
0. Adopt Abbott basin models for Reno and Eagle Val. (Carson City)- some products are available from Washoe County (Widmer).
1. Measure Vs at Carson-Valley and other unmeasured ANSS stations, as well as unmeasured geologic units (in collaboration with USGS internal projects?); do further research on geotechnical data correlation with geology.
1. Create an initial Tahoe Basin model (from work by Karlin and S. B. Smith, UCSD).
1. Investigate 3-d geology of basin floors and edges, tied into fault models, to redefine cross sections in Carson Valley, using a Carson Range fault system simple geometry model
2. Carson Val. gravity database modeling using Oppliger's compilation.
2. Investigate 3-d geology of basin floors and edges, tied into fault models, to redefine cross sections in Carson Valley, after further investigation of basin east-side faults.
2. Carson Range fault system model development (opportunity for USGS collaboration?).
2. Remodeling of Reno basin, including new wells, and Washoe Co. gravity (Widmer, Oppliger).
2. More completely address soil nonlinearity- assemble existing plus new models (Anderson, Luke).

***Las Vegas Metro Area (incl. Pahrump Val.) data needs:***

0. Adopt Langenheim Las Vegas Valley basin model.
0. Adopt a geotechnical layer based on Scott et al. (2006).
0. Adopt as background crustal and upper-mantle P-S tomography by Hearn, and Moschetti (there are too few stations for LVV-Pahrump detail model).
0. Adopt for Pahrump Val. impedance-contrast depths the results on industry lines from D. Donovan, J. Hoffard UNR theses.
0. Depths of impedance contrasts R1, R2, and R3 are available from reflection, refraction in Las Vegas Val. by Snelson.
0. Deep basin (>100 m) Vs results are available from UNLV thesis- Snelson student.
1. Need better-defined geology of Pahrump basin edges- from better definition of fault models.
2. Develop Roach Val., Coyote Springs basin models.
2. Collaborate with Air Force on Nellis Base assessments.

2. Geotechnical correlation with geology from UNLV (Taylor & Luke)?
2. Measure Vs at all ANSS sites (w/ USGS collaboration?)
2. Vet and improve inter-station phase velocity results, also empirical Green's functions; include Abbott's Pahrump array (Sandia Labs collaboration).
2. More completely address soil nonlinearity- assemble existing plus new models (Luke, Anderson).

*Data needs the group asks to USGS to make a priority for internal projects*– The working group discussed what priority data needs that USGS internal projects could most sensibly provide. We are glad to see the Survey turning its attention to the Nevada urban areas, and our consensus for the most critical collaborations is for the following:

- In the Reno-Sparks basin we rely on Stephenson's group at the USGS to profile the basin and derive the depths of the impedance contrasts R1, R2, and R3 from reflection surveys. Stephenson has indicated that he may be able to start this in the summer of 2009.
- Around the Las Vegas metro area we need new permanent seismic stations for tomography and site response, as well as monitoring and location of earthquakes in Las Vegas Valley. The background crustal and upper-mantle P-S tomography by Hearn, and Moschetti suffer from too few stations for any detail in a LVV-Pahrump model.

*Discussion of the form and use of the WGBCVM*– Initial discussion was on the value of having an "Official Version" of the CVM, versus having unofficial versions from individual CVM contributors. Based on the experience of SCEC for Southern California, the USGS for Northern California, and with the Wasatch Front CVM, a consensus was formed that there should be one "Official Version." Datasets will be included in the official version if the difference they make on ground motions is significant when tested by the WGBCVM working group.

The next discussion was on the form of the WGBCVM. The decision on the database method affects how collaborations with other groups can be pursued. Adopting Earthvision would encourage collaboration with LLNL and the Northern California CVM group, but the cost of Earthvision software is prohibitive at \$75,000 per license. Louie's MA-CME is open-source and free, but much development is needed before the code can represent some of the details found in other CVMs. The working group was particularly inspired by the codes Magistrale has built for SCEC and for the Wasatch Front CVM. Although merging and smoothing of disparate data sets require much handwork, Magistrale has produced excellent and effective CVM products already, which have been a basis of validated predictions of seismic ground motions (e.g., Olsen, 2000; Olsen et al., 2003).

Other issues debated included how to develop understanding of model uncertainties; these can be subjects for NSF and DOE proposals. It is important to think about how to honor the needs of the ultimate customers, which is the public being protected from earthquake disasters. Along with the NEHRP-NIW program funding a project to build the CVM, the working group emphasizes the importance of validating the CVM against recorded ground motions.

*Potential collaborations to investigate*– Frank Monastero inspired the group with this list of possible collaboration opportunities, given here with additions discussed:

- Utilities: Sierra Pacific Power Co., Nevada Power, Truckee Meadows Water Authority, Southern Nevada Water System, Southern Nevada Water Authority
- FEMA (interested in security of dams, Calif. power transmission), NV-Div. Emergency Management
- Army Corps of Engineers, US Bureau of Reclamation, Army (commander of Hawthorne Depot), Navy, Air Force (LVV-Nellis base engineer Colonel, motivation is mission integrity & force readiness)
- Gas pipelines, oil pipelines
- Builders: Northern Nevada Builders Assoc., Western Nevada Builders Assoc., Southern Nevada Builders Assoc., Assoc. Engineering Geologists regions
- Nuclear Regulatory Commission
- Nevada Dept. of Transportation
- DOE- YMP, Nat'l. Nuclear Security Agency, GMSEC- NSO
- AEG, ASCE, SEASoN, Reno & Las Vegas Chapters; Amer. Institute of Architects
- Nevada public works board, fire marshals
- Multi-hazard efforts, emergency managers

The WGBCCVM working group needs a document to take to potential collaborators and funders. A version of this white paper should be vetted by the Nevada Earthquake Safety Council and presented at public forums in Reno and Las Vegas.

*FY09 Consensus Priorities*– After this intensive discussion of priorities, the group found a consensus on the following priorities for the FY09 USGS NEHRP external program RFP. These priorities were posted on the workshop site ([www.seismo.unr.edu/gbccvm](http://www.seismo.unr.edu/gbccvm)) and sent to NIW region coordinator Mark Peterson on Jan. 24, 2008:

We recommend that these revised FY 2009 Nevada priorities be posted for the next round of proposals due May 2008. The principal change is to substitute the priority that begins with the words: “Improve and validate 3D velocity models...” with the following consensus priorities:

- Develop a Western Basin & Range Community Velocity Model (CVM):
  - To cover the entire region with existing geological and geophysical information, plus embedded details for the Reno-Carson City Urban Corridor (including Tahoe), and the Las Vegas Metro area (including Pahrump Valley).
  - Validate the CVM during its development by generating synthetics from the 3-d model for recordings of moderate earthquakes and explosions. Revise the model to incorporate validation results.
- Develop new data for incorporation into the Western Basin & Range CVM:
  - Western Basin & Range Region
    - Develop a regional map of shallow shear-wave velocities ( $V_{s30}$ ) and densities from existing measurements for inclusion in the CVM, and for use in ShakeMap.
  - Las Vegas Metro Area (including Pahrump Valley)



- Construct a model for the structure of the edges of the Pahrump basin, consistent with fault models, for inclusion in the CVM.
- Obtain generalized depths of important impedance contrasts in Las Vegas Valley for inclusion in the CVM.
- Reno/Carson City Urban Corridor (including the Lake Tahoe basin)
  - Construct cross sections of the significant basins, consistent with available geological and geophysical data sets, for inclusion in the CVM.
  - Collect shallow shear-wave velocity ( $V_{s30}$ ) measurements at uncharacterized ANSS sites, and on geologic units that are not well characterized.
  - Compile and develop a detailed shallow shear-velocity model for the Urban Corridor using existing geological and geophysical data.
  - Obtain generalized depths of important impedance contrasts in the Urban Corridor.

The following additional Nevada priorities appeared in the FY08 document, and the Nevada CVM Working Group came to a consensus to modify them as follows:

- **Delete:** ~~Test the sensitivity of shaking to velocity structure at various scales~~
  - ~~As a guide to identifying those parts of the velocity model most in need of further study~~
- **Keep:** Use ANSS data in Reno/Carson, and Las Vegas
  - To find empirical site response, validate predictions of 3D velocity models, and improve ground-motion prediction approaches.
- **Update:** Prepare scenario ground-motion models based on waveform modeling with the *Western Basin & Range CVM*.
  - For earthquakes on major faults affecting Reno/Carson and Las Vegas.

## References

- Abbott, R.E. and Louie, J.N., 2000, Case history: depth to bedrock using gravimetry in the Reno and Carson City, Nevada, area basins: *Geophysics*, 65(2), 340-350.
- Langenheim, V. E., Grow, J., Miller, J. J., Davidson, J. D., and Robison, E., 1998, Thickness of Cenozoic deposits and location and geometry of the Las Vegas Valley shear zone, Nevada, based on gravity, seismic-reflection, and aeromagnetic data: *U. S. Geological Survey Open-File Report OF 98-0576*, 32 pp.
- Larsen, S., Wiley, R., Roberts, P., and House, L., 2001, Next-generation numerical modeling: incorporating elasticity, anisotropy and attenuation: Society of Exploration Geophysicists Annual International Meeting, *Expanded Abstracts*, 1218-1221.

- Magistrale, H., S. Day, R. W. Clayton, and R. Graves, 2000, The SCEC Southern California Reference Three-Dimensional Seismic Velocity Model Version 2: *Bulletin of the Seismological Society of America* 90(6B), S65–S76.
- Olsen, K. B., 2000, Site amplification in the Los Angeles Basin from three-dimensional modeling of ground motion. *Bulletin of the Seismological Society of America*, 90(6B), S77-S94.
- Olsen, K. B., S. M. Day, and C. R. Bradley, 2003, Estimation of Q for Long-Period (>2 sec) Waves in the Los Angeles Basin: *Bulletin of the Seismological Society of America*, 93, 627-638.
- Pancha, Aasha, John G. Anderson, and John N. Louie, 2007, Characterization of near-surface geology at strong-motion stations in the vicinity of Reno, Nevada: *Bulletin of the Seismological Society of America*, 97, 2096-2117.
- Saltus, R. W., and Jachens, R. C., 1995, Gravity and basin-depth maps of the Basin and Range Province, Western United States: U.S. Geological Survey, *Geophysical Investigations Map, Report: GP-1012*, 1 sheet.
- Scott, J. B., M. Clark, T. Rennie, A. Pancha, H. Park and J. N. Louie, 2004, A shallow shear-wave velocity transect across the Reno, Nevada area basin: *Bulletin of the Seismological Society of America*, 94, 2222-2228.
- Scott, J. B., T. Rasmussen, B. Luke, W. Taylor, J. L. Wagoner, S. B. Smith, and J. N. Louie, 2006, Shallow shear velocity and seismic microzonation of the urban Las Vegas, Nevada basin: *Bulletin of the Seismological Society of America*, 96(3), 1055-1067, doi: 10.1785/0120040093.
- U.S. Geological Survey and California Geologic Survey, 2006, Quaternary fault and fold database for the United States, accessed 2/1/2007, from USGS web site: <http://earthquakes.usgs.gov/regional/qfaults/>.
- Wald, D. J., and T. I. Allen, 2007, in press, Topographic slope as a proxy for seismic site conditions and amplification: *Bulletin of the Seismological Society of America*. (earthquake.usgs.gov/vs30)



**Nevada Great Basin  
Community Velocity  
Model Workshop  
Schedule**

*January 14-15, 2008 at  
the University of Nevada,  
Reno*



**Monday 1/14/2008**

8:00	John Louie NSL, UNR louie-at-seismo.unr.edu	<a href="#">Introduction, thanks, and workshop objectives</a>
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**Status of CVM efforts in Nevada**

8:20	John Louie NSL, UNR louie-at-seismo.unr.edu	<a href="#">Crustal thickness in the northern Sierra and northern Nevada</a>
8:40	John Anderson NSL, UNR jga-at-seismo.unr.edu	<a href="#">The need for accurate velocity models in Nevada network seismology</a> ( <i>Chuetsu animation</i> ) ( <i>TeraShake animations: <a href="#">NW</a>; <a href="#">SE</a></i> )
9:00	David von Seggern NSL, UNR vonseg-at-seismo.unr.edu	<a href="#">Joint seismic tomography/location inversion for the Reno-CarsonCity area</a> ( <i>Vp animations: <a href="#">E-W</a>; <a href="#">S-N</a></i> )
9:20	Arthur Rodgers LLNL rodders7-at-llnl.gov	<a href="#">3-d models of the southern Great Basin, and shaking in Las Vegas</a> ( <i>Barnwell animation</i> )

9:40-10:20 *Break for coffee, workshop mechanics, and discussion*

10:20	Barbara Luke UNLV barbara.luke-at-unlv.edu	Shear wave velocity profiling in Las Vegas valley
10:40	Aasha Pancha NSL, UNR pancha-at-seismo.unr.edu	<a href="#">Need for an accurate Reno velocity model to understand amplification in the Reno Basin</a>
11:00	Chris Henry NBMG, UNR chenry-at-unr.edu	<a href="#">Three-dimensional geologic complexity of the Truckee Meadows basin from geologic mapping</a>
11:20	Lee Liberty Boise State lml-at-cgiss.boisestate.edu	Case study for building a CVM: Geophysical characterization of the Hot Creek Valley, central Nevada
11:40	Morgan Moschetti U. Colorado, Boulder morganm-at-ciei.colorado.edu	<a href="#">Application of empirical Green's functions in the construction and validation of the Great Basin Community Velocity Model</a>

12:00-1:30 *Working lunch and discussion*

1:30	John Louie NSL, UNR louie-at-seismo.unr.edu	<a href="#">The MA-CME modeling environment and initial scenario ground-motion computations for Reno and Las Vegas (NV scenario animations)</a>
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#### **USGS objectives, funding, internal & external projects, and collaborations**

1:50	Jack Odum USGS odum-at-usgs.gov	<a href="#">The USGS and the development of the Nevada Great Basin Community Velocity Model</a>
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#### **Status and results of Utah CVM**

2:10	Harold Magistrale SDSU magistra-at-mail.sdsu.edu	The Wasatch Front CVM
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#### **Other CVM efforts- their advice**

2:40	Robert Sydnor Engineering Geologist RHSydnor-at-aol.com	<a href="#">Applications of shear-wave velocity to the Building Code</a>
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3:00-3:40	<i>Break for coffee and discussion</i>	
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3:40	Chris Wills CGS Chris.Wills-at-conservation.ca.gov	<a href="#">Preparing maps of Vs30 based on geologic maps</a>
4:10	Arthur Rodgers LLNL rogers7-at-llnl.gov	The 1906 modeling effort, and lessons learned
4:40	Louie for G.R. Keller U. Oklahoma grkeller-at-ou.edu	<a href="#">Open Earth Framework: Building 3-d models via integration of geological and geophysical data</a>
4:50	John Louie NSL, UNR louie-at-seismo.unr.edu	<a href="#">CVM efforts in Wellington, New Zealand</a>

5:00	<i>Questions, wrap-up, charge for Tuesday discussions</i>	
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#### ***Tuesday 1/15/2008***

8:00-9:40	Discussion- What results do we need in a Nevada CVM for ground-motion prediction? Who will use the CVM, and how?	
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9:40-10:20	<i>Break for coffee, workshop mechanics, and discussion</i>	
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10:20-12:00	Discussion- How do we obtain the necessary data and results? What methods are cost-effective enough to be funded? What collaborations are needed?	
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12:00-3:00	Working lunch and discussion- Write and order Nevada CVM priorities for NEHRP RFP	
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3:00	<i>Adjourn</i>
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Feb. 11, 2008  
J. Louie

**Nevada Great Basin Community  
Velocity Model Workshop  
January 14<sup>th</sup> and 15<sup>th</sup>, 2008  
Participants**

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For participants listed in gray text, space was held but they were not able to attend.



## Western Basin and Range CVM Followup Workshop Schedule

*Monday November 3, 2008 at the University of Nevada, Reno*

### Joe Crowley Student Union, Room 402

Time	Name	E-mail	Title
8:00	John Louie & Lori McClelland	louie_at_seismo.unr.edu, mcclella_at_unr.edu	Welcome and workshop mechanics
8:15	Sydnor, Bob	RHSydnor_at_aol.com	Shear-wave velocity as a proxy for liquefaction analysis
8:45	Tibuleac, Ileana	ileana_at_seismo.unr.edu	Reno basin velocity structure from noise crosscorrelations
9:15	Liberty, Lee	lml_at_cgiss.boisestate.edu	Geophysical characterization of the Hot Creek Valley, central Nevada
9:45	<i>Break</i>		<i>Discussion</i>
10:15	Abbott, Robert	reabbot_at_sandia.gov	A nascent project to develop a site-conditions map of the Nevada Test Site
10:45	Tanimoto, Toshiro	toshiro_at_geol.ucsb.edu	Deriving shallow S-wave velocity structure from seismic noise
11:15	Stephenson, Bill J.	wstephens_at_usgs.gov	High-resolution basin imaging for CVMs and urban seismic hazard maps
11:45	Louie, John	louie_at_seismo.unr.edu	Using a preliminary WBRCVM to compute ground motions from the Wells and Mogul events
12:15	<i>Lunch</i>		<i>Discussion Continues</i>
1:30	Dave Hill	hill_at_usgs.gov	Long Valley in-a-box
1:45	Moschetti, Morgan	morganm_at_ciei.colorado.edu	Application of empirical Green's functions in the construction and validation of the Great Basin Community Velocity Model
2:15	Magistrale, Harold	magistra_at_mail.sdsu.edu	The Wasatch Front CVM and prospects for a WBRCVM
2:45	Peterson, Mark	mpetersen_at_usgs.gov	The FY09 USGS NEHRP-NIW program
3:15	<i>Break</i>		
3:45	<i>Discussion</i>		<i>Planning for FY09 WBRCVM Activities</i>
5:00	<i>Adjourn</i>		

To: Nevada Earthquake Safety Council  
From: John Louie, Univ. of Nevada, Reno [louie@seismo.unr.edu](mailto:louie@seismo.unr.edu)  
Date: January 26, 2009  
Subject: USGS-sponsored working group focuses on predicting earthquake-shaking hazards in Nevada

The USGS has been conducting research into physics-based modeling of shaking from scenario earthquakes for Seattle and Salt Lake City, in concert with similar efforts for northern and southern California. Since the USGS-NEHRP program has construction of new earthquake-hazard maps for Reno and then Las Vegas as top regional priorities, they have generously funded the formation of a broad-based working group to start up a physics-based shaking-prediction effort for Nevada.

Such scenario modeling requires assembling available geological, geophysical, and geotechnical results for the region into a Community Velocity Model or "CVM," and validating intensive CVM computational results against recorded shaking data. The Western Basin & Range CVM Working Group convened in Reno in January and November of 2008, and has recommended that the USGS begin modest funding of a CVM construction and validation effort. Technical details are at [www.seismo.unr.edu/wbrcvm](http://www.seismo.unr.edu/wbrcvm), and the specific recommended funding priorities are attached.

WBRCVM construction and validation will lead over the next 5 years to more realistic Reno and Las Vegas hazard maps, as well as a more effective selection of time series for use in structural design. The working group welcomes the involvement of NESC members in three ways: 1) through contributions of geological, geophysical, and geotechnical data to the CVM from the Reno-Carson Urban Corridor (including Tahoe) and the Las Vegas Metropolitan Area (including Pahrump Valley); 2) by helping us define the desired products from the physics-based modeling needed by the engineering and emergency-response communities, and evaluating the effectiveness of our results; and 3) by helping us leverage the small amounts of USGS funds available, to appeal to a broad selection of possible sponsors for such work.

To: Mark Petersen  
NEHRP-NIW Regional Coordinator, U.S. Geological Survey, Denver  
Jon Price  
Nevada State Geologist and Director, Nevada Bureau of Mines and Geology  
From: John Louie, Convener of the Western Basin & Range CVM Workshops  
Date: Nov. 3, 2008

Subject: **Consensus Nevada priorities from the Western Basin & Range CVM Followup Workshop, Nov. 3, 2008**

For USGS NEHRP-NIW FY 2008 external research program proposals, the location <http://www.nbmng.unr.edu/eq/priorities.pdf> offered a list of specific priorities for Nevada. These priorities were not updated for FY 2009. As part of the discussions during the Western Basin & Range CVM Workshop and Followup held on January 14 and 15, and on November 3, 2008, on the campus of at the University of Nevada, Reno, and sponsored by the USGS NEHRP-NIW program, the assembled working group (list attached) came to a consensus to make the following modifications to the previous Nevada priorities. We recommend that these revised FY 2010 Nevada priorities be posted for the next round of proposals due May 2009:

The principal change is to substitute the priority that begins with the words: “Improve and validate 3D velocity models...” with the following consensus priorities:

- Continue development of a Western Basin & Range Community Velocity Model (CVM):
  - To provide for urban hazard mapping in the Reno-Carson City Urban Corridor (including Tahoe and Fallon) as a first priority, and to cover the entire region with existing geological and geophysical information. The Las Vegas Metro area (including Pahrump Valley and the I-15 corridor) is the next priority. Events outside the urban areas, with propagation through intervening basins, are crucial model scenarios.
  - Validate the CVM during its development by generating synthetics from the 3-d model to compare with recordings of moderate earthquakes and explosions, and EGFs. Validation should show where critical data needs lie. Revise the model to incorporate validation results.
- Develop new data for urban hazard mapping (goal of 1-sec waves), and incorporation into the Western Basin & Range CVM:
  - Reno/Carson City Urban Corridor (including the Lake Tahoe basin and the Fallon area)
    - Construct cross sections of the significant basins, consistent with available geological and geophysical data sets, for inclusion in the CVM. A priority is to capitalize on recordings of the M5 4/25/08 and other Mogul events.
    - Collect shear-wave velocity measurements (e.g.,  $V_{S30}$ ) at uncharacterized ANSS sites, on geologic units that are not well characterized, and at urban basin depths below 300 m.

- Compile and develop a detailed shallow shear-velocity model for the Urban Corridor using existing geological and geophysical data.
- Obtain generalized depths of important impedance contrasts in the Urban Corridor.
- Las Vegas Metro Area (including Pahrump Valley)
  - Construct a model for the structure of the edges of the Pahrump basin, consistent with fault models, for inclusion in the CVM.
  - Obtain generalized depths of important impedance contrasts in Las Vegas Valley for inclusion in the CVM.
- Western Basin & Range Region
  - Aggregate seismic velocity and density information from existing measurements for inclusion in the CVM, and for use in ShakeMap.

The following additional Nevada priorities appeared in the FY08 document, and the Nevada CVM Working Group came to a consensus to modify them as follows:

- **Delete:** ~~Test the sensitivity of shaking to velocity structure at various scales~~
  - ~~As a guide to identifying those parts of the velocity model most in need of further study~~
- **Keep:** Use ANSS data in Reno/Carson, and Las Vegas
  - To find empirical site response, validate predictions of 3D velocity models, and improve ground-motion prediction approaches.
- **Update:** Prepare scenario ground-motion models based on waveform modeling with the *Western Basin & Range CVM*.
  - For earthquakes on major faults affecting Reno/Carson and Las Vegas.

cc:  
 Nevada Earthquake Safety Council  
 John Anderson, *Director*, UNR Seismological Laboratory  
 Barbara Luke & Wanda Taylor, UNLV  
 WBRCVM Working Group

**Followup Workshop attendees (many UNR attendees did not register):**

<b>Name</b>	<b>E-mail</b>	<b>Address</b>	<b>Request for honorarium ?</b>	<b>Presenta tion?</b>
<b>Abbott, Robert</b>	<a href="mailto:reabbot@sandia.gov">reabbot@sandia.gov</a>	Sandia National Labs PO Box 5800 MS 1168 Albuquerque, NM 87185-1168	No	yes
<b>Cashman, Pat</b>	<a href="mailto:pcashman@mine.s.unr.edu">pcashman@mine.s.unr.edu</a>		no	no
<b>Emmitt, Ryan</b>	<a href="mailto:emmittf@nv.doe.gov">emmittf@nv.doe.gov</a>	2621 Losee Rd, North Las Vegas, NV. 89030 M/S: NLV075		
<b>Hill, David P.</b>	<a href="mailto:hill@usgs.gov">hill@usgs.gov</a>	Scientist in Charge, Long Valley Observatory U.S. Geological Survey MS 910, 345 Middlefield Rd. Menlo Park, CA 94025 1910 University Dr CGISS Department		
<b>Liberty, Lee</b>	<a href="mailto:lm1@cgiss.boisestate.edu">lm1@cgiss.boisestate.edu</a>	Boise State University Boise, Id 83725-1536	Yes	Yes
<b>Lin, Guoqing</b>	<a href="mailto:glin@geology.wisc.edu">glin@geology.wisc.edu</a>	111 Weeks Hall 1215 W. Dayton St., Madison, WI, 53706	Yes	Yes
<b>Magistrale, Harold</b>	<a href="mailto:magistra@mail.sdsu.edu">magistra@mail.sdsu.edu</a>	5476 Kiowa Drive #30, La Mesa CA 91942	Yes	maybe
<b>Moschetti, Morgan</b>	<a href="mailto:morganm@ciei.colorado.edu">morganm@ciei.colorado.edu</a>	Center for Imaging the Earth's Interior Department of Physics Campus Box 390 Univ. of Colorado Boulder, CO 80309-03901	Yes	Yes
<b>Pancha, Aasha</b>	<a href="mailto:pancha@seismo.unr.edu">pancha@seismo.unr.edu</a>	200 S. Virginia Street Suite 560 Reno, NV, 89501		no
<b>Peterson, Mark</b>	<a href="mailto:mpetersen@usgs.gov">mpetersen@usgs.gov</a>	USGS, Denver Federal Center, MS 966, Box 25046, Denver, CO 80225	No	yes
<b>Rodgers, Arthur</b>	<a href="mailto:rodgers7@llnl.gov">rodgers7@llnl.gov</a>	L-205 700 East Avenue Livermore, CA 94551	Yes	Yes
<b>Stephenson, Bill J.</b>	<a href="mailto:wstephens@usgs.gov">wstephens@usgs.gov</a>		No	yes
<b>Tanimoto, Toshiro</b>	<a href="mailto:toshiro@geol.ucsb.edu">toshiro@geol.ucsb.edu</a>	Department of Earth Science University of California, Santa Barbara California 93106	Yes	Yes
<b>Von Seggern, David</b>	<a href="mailto:vonseg@seismo.unr.edu">vonseg@seismo.unr.edu</a>	N/A	No	Yes
<b>White, Robert</b>	<a href="mailto:whiterl@nv.doe.gov">whiterl@nv.doe.gov</a>	P.O. Box 98521; MS NLV075; Las Vegas, Nv.; 89193	No	No
<b>Zeng, Yuehua</b>	<a href="mailto:zeng@usgs.gov">zeng@usgs.gov</a>		No	no
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## **Paper and presentations on the WGBCVM Working Group's efforts:**

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J. N. Louie, and Magistrale, H., 2008, From data to synthesis on the cheap: the Western Basin and Range Community Seismic Velocity Model: *Eos Trans. AGU*, **89**(53), Fall Meet. Suppl., Abstract IN43A-1165.

# Assembling a Nevada 3-d velocity model: earthquake-wave propagation in the Basin & Range, and seismic shaking predictions for Las Vegas

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## Summary

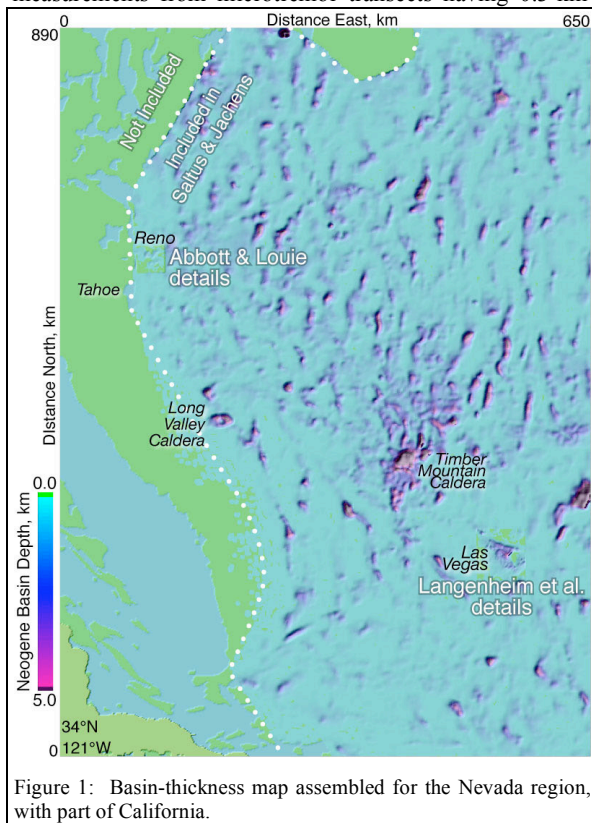
The development of an open-source 3-d modeling environment allows seismologists, explorationists, engineers, and students to predict wave propagation through geologically complex regions. The environment combines geologic and geotechnical data sets with gridding, modeling, and output specifications into portal packs for execution on standalone workstations, clusters, and supercomputing grids. A tutorial interface helps the user scale the grid to the facilities available, from small test runs to efforts requiring major resources. The ability to configure computations at a range of scales and model complexity is intended to promote wide use of advanced seismic modeling. Geologic models can include many basins in addition to the target urban basin, and detailed geotechnical information where available. To predict earthquake shaking in Nevada urban areas, the 3-d model assembles several data sets at a wide variety of scales, from regional geologic maps to shallow shear-velocity measurements from microtremor transects having 0.3-km

spacing. For Las Vegas the principal earthquake hazard is from the Furnace Creek fault system, capable of M7.5 events. Peak ground velocity (PGV) results from finite-difference wave modeling at 0.3 Hz show no obvious correlation between amplification and basin depth or dip of the basin floor. Animations of shaking show the expected strong trapping and long shaking durations within basins, as well as diffusion and scattering of energy between the many basins in the region. The two Furnace Creek scenarios tested, involving rupture away from and toward Las Vegas, produced unexpectedly different PGV in the city. Rupture directivity toward the city may amplify shaking by a factor of fifteen at some locations. Despite affecting only the very shallowest zone of models (<30 m), the Vs30 geotechnical shear-velocity shows clear correlation to 0.3-Hz PGV predictions in basins. Increasing basin thicknesses to 1.3 km correlate with increased PGV, but the basin effect at 0.3 Hz saturates for basin thicknesses greater than 1.3 km; deeper parts of the basin show variance and uncertainty of a factor of two in predicted PGV.

## Introduction

The concept of a Community Modeling Environment (CME) was developed at the Southern California Earthquake Center (SCEC) under U.S. National Science Foundation Information Technology Research sponsorship. SCEC's CME combines, in part, geologically based 3-d velocity and fault databases, developed as consensus models in the regional geophysical community (e.g., Magistrale et al., 2000), with a seismic-modeling computational engine (e.g., Olsen, 2000). The innovation of SCEC's velocity model is that it is expressed not as a preset 3-d grid but as flexible computer code, able to create grids of various extents and node spacings. This innovation simplifies the process of creating high-resolution grids for local modeling, or geographically extensive grids with larger spacings for large-area but low-frequency models. (The finer the grid spacing, the higher the frequencies that can be modeled.)

The purpose of the ModelAssembler Community Modeling Environment (MA-CME) was initially to provide a community velocity model and seismic modeling environment for Nevada urban areas (figure 1). Reno and Las Vegas are subject to earthquake hazards both from below their local basins, and from faults up to 200 km away. Thus, attacking the problems of modeling scenario events, or modeling small events for which ground-motion data have been recorded, demand running synthetic





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seismograms for a wide variety of models across a spectrum of scales.

The computations in this paper fed MA-CME output results to the E3D code (Larsen et al., 2001) from LLNL for elastic wave-propagation computation. E3D was most recently vetted for ground-shaking prediction at the March 24-25, 2004 Next Generation Attenuation (NGA) Workshop as part of the Pacific Earthquake Engineering Research Center (PEER)/SCEC 3D Ground Motion Project Team led by S. Day.

The intention of MA-CME is to make the preparation of E3D computational jobs more easy. MA-CME is an open-source, Java-based velocity-model gridding code that can integrate scattered and heterogeneous geophysical data sets. It also provides facilities for visualizing model grids and computed E3D results as maps, cross sections, and movies. Source code, installation packages, and example results for MA-CME are available free from [www.seismo.unr.edu/ma](http://www.seismo.unr.edu/ma).

### Method

ModelAssembler is essentially a pre-processor for a finite-difference wave-propagation code such as E3D, and is run

in advance of it. MA accepts geographic (latitude and longitude) locations for sources and receivers, and reads geological and geophysical data files. The MA-CME graphical user interface provides a tutorial interface to MA, helping to set up the geological model, and allows gridding and E3D computations to be set up at any scale. MA outputs 3-d grids of P velocity, shear velocity, and density, along with a control file for E3D. E3D can then be run directly on the MA outputs. The geological and geophysical data files input are all in readable text format, specify properties at points located with geographic coordinates, and do not rely on the data having any particular sorting or organization. Edits and additions to the data files are easy to make.

Within the MA-CME GUI, the interface provides the user immediate feedback on the difficulty of the computation being attempted, estimating the total memory needed for the E3D run described, the number of CPUs needed, the maximum frequency that can be computed with no grid dispersion artifacts, and the clock time likely required. For example, in a grid setup panel, an advice message pane turns green if the computation will fit on a single workstation, yellow if a small cluster of 2-50 CPUs is needed, and red if more than 50 CPUs are required.

Fundamental to ModelAssembler is the concept that low-resolution regional data sets can be superimposed by detailed local data. Grids at any scale can thus be created as composites of various results at very different scales. In Nevada, a regional data set with the thicknesses of Neogene basins sampled at 2 km spacing for the entire Basin and Range is often combined with local results from the urban basins that sample their thicknesses at 0.4 km spacing. For the Nevada model, figure 1 shows how four datasets at various scales on Neogene basin thicknesses are roughly stitched together: 1) a regional-scale geologic map at 1-km resolution, allowing basin thicknesses to be estimated from bedrock proximity, in California; 2) Saltus and Jachens's (1995) USGS basin gravity inversions for the Basin and Range, including both sedimentary and Tertiary volcanic basins at 2-km resolution; 3) Abbott and Louie's (2000) Reno-area basin gravity study at 0.4-km resolution; and 4) the Langenheim et al. (1998) Las Vegas basin model from gravity, refraction, and a few deep wells, at 0.4-km resolution.

Geotechnical data sets are also incorporated, as in figure 2, despite having spacings varying from 0.1 to 0.3 km, and including isolated point measurements. MA interpolates all the disparate data sets onto a regular grid, following instructions for how one data set may take precedence over another where they overlap. For the Nevada model, three datasets are combined in this way: 1) the regional geologic map controls the default shallow geotechnical shear

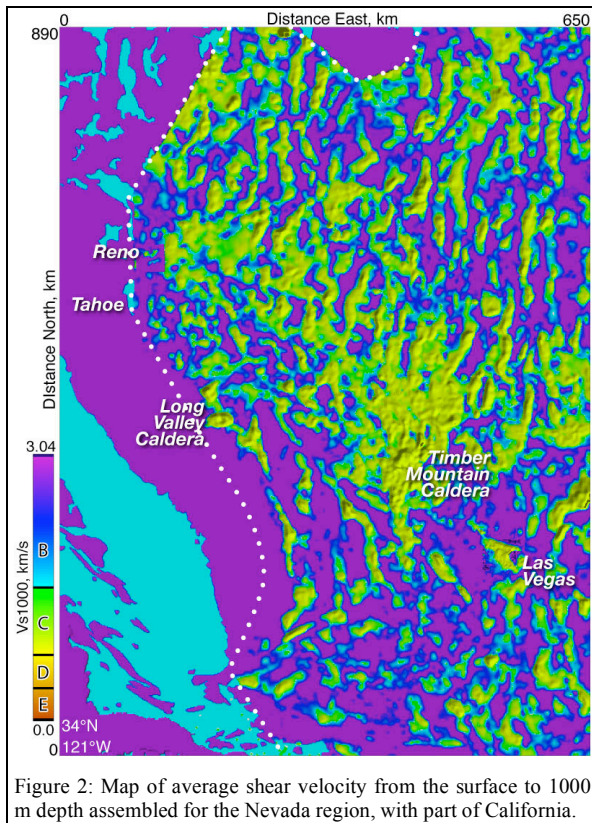


Figure 2: Map of average shear velocity from the surface to 1000 m depth assembled for the Nevada region, with part of California.

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velocity  $V_{s30}$  (the average from the surface to 30 m depth), 500 m/s for basin sites and 760 m/s for rock sites; 2) Reno refraction microtremor transect results from Scott et al. (2004) and sites measured by Pancha et al. (2007); and 3) Las Vegas refraction microtremor transect, sites by B. Luke at UNLV, stratigraphy correlated to 1145 wells by W. Taylor of UNLV and G. Wagoner of LLNL, all from Scott et al. (2006).

Each model is accompanied by a set of rules governing how the interpolations are done, how geophysical properties will vary with depth inside and outside basins, and how the properties not supplied in the data sets will be estimated from the ones that are supplied. Thus in bedrock

outside basins in most areas the rules describe a P-velocity versus depth profile  $V_p(z)$  used for earthquake locating, and equations for estimating the corresponding shear velocity  $V_s$  and density  $\rho$ . In Nevada the basin density  $\rho(z)$  profile is assumed (from oil-field measurements summarized by Saltus and Jachens, 1995) and  $V_p$  and  $V_s$  are estimated. Thus MA yields laterally homogeneous properties within basin and bedrock, although the interface between basin and bedrock can vary wildly in depth.

The task of modeling the effect of a magnitude-7.5 earthquake along the Furnace Creek fault zone on Las Vegas was given as a class exercise to senior undergraduate Liz Lenox in Fall 2006. She set up the E3D computation in MA-CME to yield 0.3-Hz waves on a 281 E-W by 251 N-S by 20-node deep grid with a  $dh=dx=dy=dz$  grid spacing of 1 km. With the 1 km spacing, MA produced the 3-d grid input for E3D, for which figure 2 maps the shear velocities of the surface nodes. The grid includes the fault zone 180 km west of Las Vegas, and the urban basin (FCFZ and LV in figure 3, upper). The figure shows that the basins near the fault in Death Valley (DV in figure 3) and under Las Vegas are smaller than the Timber Mountain caldera and the volcanic-filled rifts radiating from it (figure 1; and dark blue and black areas of figure 3, upper). Infinite Q was assumed for these scenarios.

The two rupture scenarios and fault parameters set up in MA-CME and supplied to E3D were derived from the USGS Qfaults database (USGS and CGS, 2006). The 80-km-long planar fault, extending 15 km vertically, ruptures in dextral strike-slip in two separate M7.5 scenarios: a rupture beginning at the fault's southeast end and proceeding northwest away from Las Vegas at 2.8 km/s; and a rupture beginning at the northwest end and proceeding toward the city.

Figure 3 (middle) shows a snapshot of the wave propagation 71 seconds after the origin time of the earthquake, for the scenario rupture toward Las Vegas. Three-component particle velocities are represented as colors, superimposed on a shaded-relief basin map. A red additive color is scaled to E-W motions; a green additive color to N-S motions; and a blue additive color to up-down motions. The greater the intensity of a component of shaking, the greater the intensity of the corresponding additive color. Thus dark colors, or the basin map showing through, represent low intensities of shaking, and bright colors high shaking intensities. Yellow in the basins shows intensive NW-SE or NE-SW horizontal shaking. The green waves in Las Vegas basin show intense longitudinal (Love) surface waves, and the alternating red and blue waves entering the basin from the west are Rayleigh surface waves with their radial-elliptical motions.

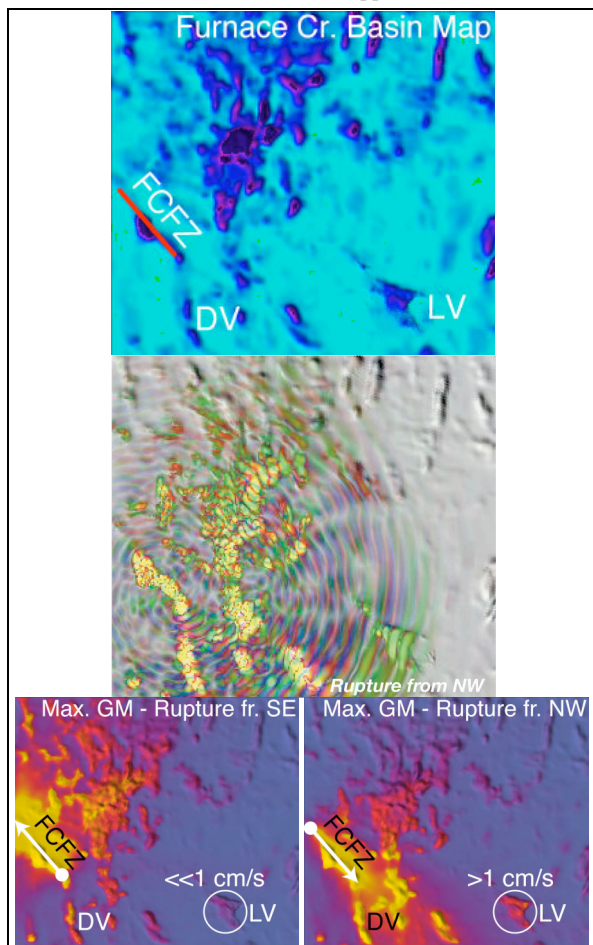


Figure 3: Maps comparing M7.5 Furnace Creek fault scenarios affecting Las Vegas. The upper image is a basin-thickness map for the region of computation; middle is a snapshot map of E3D wave propagation at 0.3 Hz through the assembled model. Below are maximum ground-motion (PGV) maps, on the left for rupture away from Las Vegas, and on the right for rupture toward the city.

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### Results

The two rupture scenarios have very different effects, as shown by the peak horizontal ground velocity (PGV) maps at the bottom of figure 3. The PGV map at left saturates with a yellow color at 1 cm/s; on the right the yellow saturation level is 2 cm/s. For rupture away from city, PGV is  $\ll 1$  cm/s in Las Vegas Valley, with damage unlikely. There is clear directivity in these long-period simulations. For rupture toward the city, PGV exceeds 1 cm/s in LVV, suggesting a possibility of damage to vulnerable structures. Basins between Death Valley and Las Vegas are spreading the directivity effect to wider angles from the fault strike than would be expected in a 1-d model. The intermediating basins are absorbing the directivity energy beams and re-radiating the energy at a broader range of azimuths. This effect is suggested by the scenario wave-propagation animations, which are available in cell-phone video format from [www.seismo.unr.edu/ma/](http://www.seismo.unr.edu/ma/).

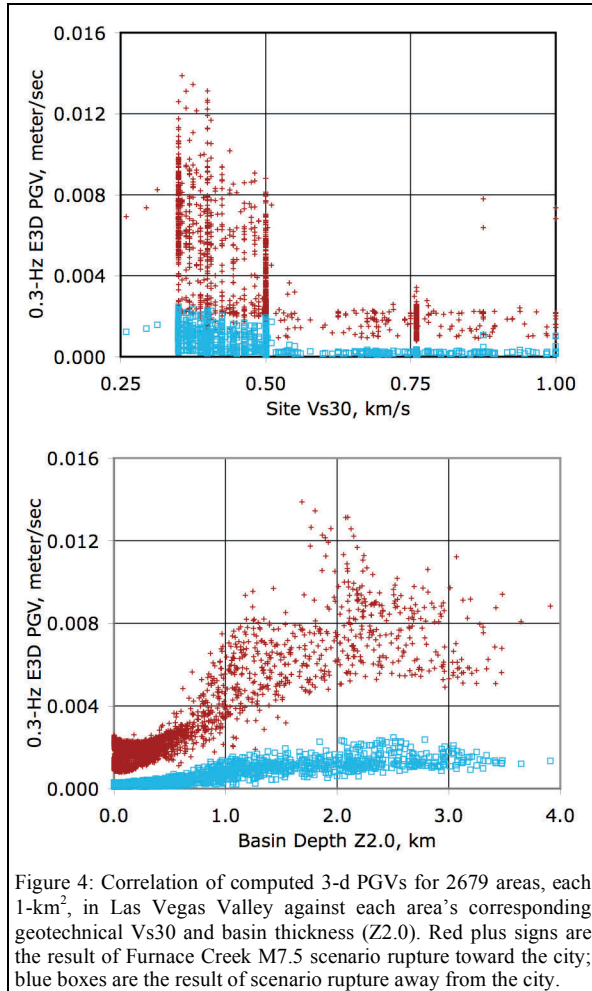


Figure 4: Correlation of computed 3-d PGVs for 2679 areas, each 1-km<sup>2</sup>, in Las Vegas Valley against each area's corresponding geotechnical Vs30 and basin thickness (Z2.0). Red plus signs are the result of Furnace Creek M7.5 scenario rupture toward the city; blue boxes are the result of scenario rupture away from the city.

Comparing the PGV maps from the two scenarios (figure 3, lower) shows the largest amplifications due to rupture directivity are in bedrock, not in basins. Yet some margins of Las Vegas basin also show 1500% amplifications. The amplifications, and the high PGV results, do not show clear correlation to basin thickness or to the dip of the basin floor. To examine the effect of geotechnical Vs30 and basin thickness on shaking, figure 4 compares the PGV computed for 2679 areas in and around Las Vegas, each 1-km<sup>2</sup>, for both rupture scenarios. Despite the wavelengths of this 0.3-Hz, 1-km grid scenario computation being more than fifty times the 30-m depth of the geotechnical Vs30 data, there appears to be a correlation of increasing PGV with decreasing Vs30 below 0.5 km/s, in the basin. The scatter or variance of PGV is, however, at least as large as the effect of Vs30, at a factor of two or three. PGV appears to correlate well with basin thickness in Las Vegas in figure 4, at least for thicknesses less than about 1.3 km. Thicker parts of the basin show a larger scatter, or variance in PGV, of a factor of two.

### Conclusions

Development of the ModelAssembler Community Modeling Environment allows non-specialists to set up complex 3-d grids for advanced wave-propagation computation. A Nevada 3-d velocity model, assembled from many disparate geological, geophysical, and geotechnical data sets at a wide range of scales, allows prediction of ground shaking in Las Vegas from scenario earthquakes in the region. Rupture directivity, broadened by the interaction of intermediary basins, has the greatest influence on computed ground motions at 0.3 Hz. Within basins, the geotechnical Vs30 as well as the basin thickness at a site play important roles in the computed ground motion. The large variance of the computed motions with respect to Vs30 and thickness, along with maps of peak ground motions, suggest that very scenario-dependent path and geometric wave-propagation effects such as lens focusing are also important.

### Acknowledgments

Shawn Larsen of LLNL assisted tremendously in creating a Nevada CME by training UNR students in the use of E3D, and installing it on facilities in the Nevada Seismological Lab. UNR undergraduates who participated in class exercises with MA-CME were Amr Wakwak, Rei Arai, and Liz Lenox, who set up and computed the Furnace Creek scenario. The author is indebted as well to colleagues Barbara Luke and Wanda Taylor at UNLV, Catherine Snelson at NMT, and Arthur Rodgers and David McCallen at LLNL.

## Nevada 3-D Velocity Model & Shaking Predictions

### References

- Abbott, R.E. and Louie, J.N., 2000, Case history: depth to bedrock using gravimetry in the Reno and Carson City, Nevada, area basins: *Geophysics*, 65(2), 340-350.
- Langenheim, V. E., Grow, J., Miller, J. J., Davidson, J. D., and Robison, E., 1998, Thickness of Cenozoic deposits and location and geometry of the Las Vegas Valley shear zone, Nevada, based on gravity, seismic-reflection, and aeromagnetic data: U. S. Geological Survey Open-File Report OF 98-0576, 32 pp.
- Larsen, S., Wiley, R., Roberts, P., and House, L., 2001, Next-generation numerical modeling: incorporating elasticity, anisotropy and attenuation: Society of Exploration Geophysicists Annual International Meeting, Expanded Abstracts, 1218-1221.
- Magistrale, H., S. Day, R. W. Clayton, and R. Graves, 2000, The SCEC Southern California Reference Three-Dimensional Seismic Velocity Model Version 2: *Bulletin of the Seismological Society of America* 90(6B), S65-S76.
- Olsen, K. B., 2000, Site amplification in the Los Angeles Basin from three-dimensional modeling of ground motion. *Bulletin of the Seismological Society of America*, 90(6B), S77-S94.
- Pancha, Aasha, John G. Anderson, and John N. Louie, 2007, Characterization of near-surface geology at strong-motion stations in the vicinity of Reno, Nevada: *Bulletin of the Seismological Society of America*, 97, 2096-2117.
- Saltus, R. W., and Jachens, R. C., 1995, Gravity and basin-depth maps of the Basin and Range Province, Western United States: U.S. Geological Survey, Geophysical Investigations Map, Report: GP-1012, 1 sheet.
- Scott, J. B., M. Clark, T. Rennie, A. Pancha, H. Park and J. N. Louie, 2004, A shallow shear-wave velocity transect across the Reno, Nevada area basin: *Bulletin of the Seismological Society of America*, 94, 2222-2228.
- Scott, J. B., T. Rasmussen, B. Luke, W. Taylor, J. L. Wagoner, S. B. Smith, and J. N. Louie, 2006, Shallow shear velocity and seismic microzonation of the urban Las Vegas, Nevada basin: *Bulletin of the Seismological Society of America*, 96(3), 1055-1067, doi: 10.1785/0120040093.
- U.S. Geological Survey and California Geologic Survey, 2006, Quaternary fault and fold database for the United States, accessed 2/1/2007, from USGS web site: <http://earthquakes.usgs.gov/regional/qfaults/>.